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Fuel Consumption Tabulation in Laboratory Conditions

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***Abstract*— This paper examines the fuel economy displayed by passenger vehicles and attempts to connect vehicular fuel consumption to such easily measurable parameters as vehicle speed, acceleration, gear and throttle position. The central contention is to understand how fuel consumption is connected to driving parameters in order to utilise such findings to reduce vehicle fuel consumption in future vehicle design. The New European Drive Cycle (NEDC) has been utilised as the testing framework to derive the mathematical relationship between fuel consumption and measurable driving parameters. The NEDC was simulated under laboratory conditions, and driving parameters together with the fuel consumption were measured. A few driving phases were identified so that any drive cycle may be composed by these phases; and mathematical relationships have been fitted on measured data for each of the phases.**

***Keywords*— NEDC, standard driving cycle, mathematical model, real life driving, testing.**

I. INTRODUCTION

The world population is 6.5 billion at the moment and rising. Climate change has caused widespread greenhouse effects like global warming, higher acid levels in oceans and reduced ice cover at the poles (Harrabin, 2013). The major causes of greenhouse effect are the by-products of industrialization, and especially carbon dioxide (Samimi & Zarinabadi, 2011). The level of carbon dioxide, the main constituent of emission by vehicles, is linked to consumption of fuel by the vehicle. Due to this there is need to regulate the amount of greenhouse gases that are emitted into the atmosphere and this is effective by fuel economy.

The fuel economy (FE) of any vehicle can be calculated as a ratio of distance travelled per unit volume of fuel consumed or as the ratio of fuel consumption per distance travelled (GFEI, 2013). Fuel economy standards can be of various forms such as litres of fuel consumed per hundred kilometres of distance travelled or distance travelled per unit volume of vehicle fuel (An, et al., 2011, p. 4).

The regulations pertaining to fuel economy followed by the four largest automobile markets, namely, the US, the EU, Japan and China differ significantly from each other leading to a lack of global standards on the issue (An, et al., 2011, p. 4).

Research has shown that road network as well as traffic conditions tend to impact diver's choices of driving. An eco-driving style was shown as being dependant on acceleration, speed, change of gears and decleration (Ericsson, 2001). Chasis dynamometer based testing for vehicle emissions has been carried out and it has been found that the emissions per unit distance depend on vehicle speed, idling or stop patches as well as acceleration and fuel type (Andre & Rapone, 2009).

This paper will focus on developing a method for the estimation of fuel consumption of passenger cars as a step toward improving the quality of life in the urban centres. In particular, laboratory driving observations will be used to propose a formulation for predicting fuel consumption under different driving phases when the vehicle speed, acceleration and throttle position are known.

II. FUEL ECONOMY

Fuel economy has been found to play an important role in the reduction of greenhouse gases and especially carbon dioxide. Due to this, it is pursued by countries seeking to reduce their levels of emissions. Automobile markets as well as manufacturers need to consider the fuel economy set standards within a market or country in making and distributing more efficient vehicles. There has been a shift in the priority of improving fuel economy with preference to reducing the emission of greenhouse gases by vehicles as a way of reducing the greenhouse effect. Even with the renovation of fuel economy standards in developed countries, the increasing demands on oil and increased emission of greenhouse gases is still a major challenge which is yet to be fully addressed (An, et al., 2011).

Fuel economy can be measured mainly by the amount of fuel consumed in order to cover a given distance by an automobile which differs from car to car (GFEI, 2013).

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This is achieved by the use of drive cycles with consideration for external factors that may affect results. These factors include different designs of cars which give varying results and varying operating conditions. Operating conditions either on a highway, an urban environment or a combination of both, would have different results on driving cycles even on the same vehicle. Several factors that influence the fuel economy of a vehicle include the engine characteristics, gear train characteristics, weight and aerodynamics, rolling resistance, driving cycle and driver habits.

There has been a global initiative aimed at reducing the fuel consumption globally from highs of 8 litres for every 100 km corresponding to 29.4 mpg down to 4 litres corresponding to 58.8 mpg for every 100 km in the next 40 years (GFEI, 2013). An adoption of similar fuel economy regulations by major automobile markets which differ significantly would serve to standardize the issue globally (An, et al., 2011). While increasing fuel efficiency in vehicles would increase economic costs to the customer, the ultimate improvements on automobile would be of considerable economic benefit to both the manufacturer and customer. The customer would save more on fuel expenses while the manufacturer would save on potential expenses on penalties for failing to comply with the international fuel efficiency standards. The environment would be the greatest winner in that the emissions of carbon would be reduced considerably.

III. Drive Cycle

Gas emission from vehicles is a big contributor to the overall concentration of greenhouse gases in the atmosphere and especially carbon dioxide. Green house gas emissions are responsible for both global warming and the resulting climate change patterns. Global warming is increasing the global temperatures incrementally annually. Moreover, climate based disturbances such as floods, droughts etc. are threatening the survival of entire communities. Vehicle exhausts are one of the major contributors of greenhouse gases globally. As a response to this threat to the environment, major vehicle markets are introducing standards to ensure fuel economy in their countries with the main aim of reducing the emission of greenhouse gases from vehicles.

A number of different measures such as the introduction of hybrid vehicles and engines with lower emissions have been initiated to reduce the scale and contribution of vehicle exhaust. Fuel economy which is measured by the amount of fuel consumed per unit distance by an automotive is enforced by the use of drive cycles. Factors that would result in differing observations in the same vehicle are noted and the vehicle is tested in different environments such as on a highway, an urban region or a combination of both. Several factors that influence the fuel economy of a vehicle include the engine characteristics, gear train characteristics, weight and aerodynamics, rolling resistance, driving cycle and driver habits (GFEI, 2013).

IV. Laboratory Simulation Of Drive Cycles

A test rig was utilised to test vehicles which is located in the advanced Automotive Laboratory at University of Huddersfield. The test rig is equipped with two AAB 132Kw AC Dynamometers, with a 4 axis robot gear shift all controlled by sierra CP Engineering's V14 software. A thorough comparison of various dynamometers was carried out in order to ascertain the optimal dynamometer for the current research. As a consequence of this investigation, a generator type dynamometer was found to be the best possible research tool.

In order for the correct load to be applied to the engine as if it were in the vehicle, the system runs in Road law which enables the dynamometers to change depending on the aerodynamic load and tyre frictional forces that would be experienced. The system is integrated with speed, pressure, fuel and temperature transducers to enable all aspects of the power train to be measured accurately. The engine utilised in the testing is a 2005 Nissan Micra 4 cylinder 1.4L16v engine that is attached to a standard 5 speed manual gearbox. The engine and its drivetrain is instrumented with various sensors and the required drive cycles were programmed using the Cadet V14 software. The sensors integrated with the testing equipment included pressure, temperature, velocity, acceleration etc. so that reliable data could be extracted for analysis.

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Figure 1 - Test Rig Employed For Engine Testing For The Current Research

A number of different logged and derived parameters were ascertained in order to verify the fuel consumption at various engine loads. The various primary parameters noted for this study were the throttle position, developed torque, engine head assembly, coolant and oil temperatures, crank angle, shaft position, fuel emissions and engine speed. In addition, a number of other engine parameters were logged such as the combustion pressure, engine component acceleration, vibration levels, stress levels of components, intake and exhaust pressure, ignition timing, valve lift, engine knocking etc. These parameters were manipulated in order to decipher a fitting mathematical model for various engine operating ranges. Moreover, these parameters were manipulated to find out the fuel consumption at various performance levels of the engine.

Figure 2 - Software Used For Monitoring Parameters During Testing

A. Air and Water Cooling

The excess energy produced by the engine was removed using the coolant as well as engine oil. Since the engine was stationary during testing, air had to be provided to assist cooling. For this purpose, two Bowman heat exchangers, with a controlled water supply that is cooled via a 500kW air blast cooler were utilized using a pneumatically controlled three way valve using a PID loop.

B. Fuel Flow

Fuel flow tends to vary transiently as the engine testing proceeds. Fuel flow was measured along with fuel temperature and pressure through a PID loop reporting to the V14 software. The system's maintained accuracy remained ±0.7%.

C. Speed Measurement

Speed is typically measured using a variable reluctance sensor that operates on inductive principles. Gear teeth are employed to register speed on an induction type probe. For further processing, the time domain is converted into the frequency domain which is then in turn converted to angular velocity. It is common to use gears with sixty teeth to perform measurements since this allows equating the measured frequency to the angular velocity. Mathematically (Gitano-Briggs, 2008, p. 44):

$$RPM = \frac{60}{n(Period)}$$

Where:

RPM is the angular velocity in revolutions per minute n is the number of teeth read by the induction probe

$Period$ is the distance between the same points on two consecutive sinusoidal waves

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Figure 3 - Typical Gear Tooth Used For Engine Speed Measurement Sourced From (Gitano-Briggs, 2008, P.44)

D. Acceleration Measurement

Acceleration measurements are not carried out directly on the dynamometer since it would tend to complicate the overall sensor interface by employing too many sensors in a limited space. A more convenient approach would be to use derived measurements such as speed to calculate the acceleration as required. The acceleration is obtained using the mathematical relationship for speed as follows:

$$Acceleration = \frac{RPM}{Time\ Step} = \frac{60}{n(Period)(Time\ Step)}$$

Where:

$Time\ Step$ is the amount of time for which the acceleration requires computation

E. Throttle Position Measurement

The throttle position is changed in order to vary engine speed and needs to be monitored continuously during testing. A variable resistor is used in order to sense the throttle position. The potentiometer is mounted on the throttle itself at one end of the throttle shaft controlled by the throttle cable. A simple 5V DC power supply is used to perform these measurements that respond to changes in resistance at the potentiometer as the throttle cable changes the throttle position.

The final output parameter is the throttle position signal (TPS) that directly measures the throttle position as a distinct voltage level when the throttle changes its state. A throttle and throttle sensor arrangement is shown below:

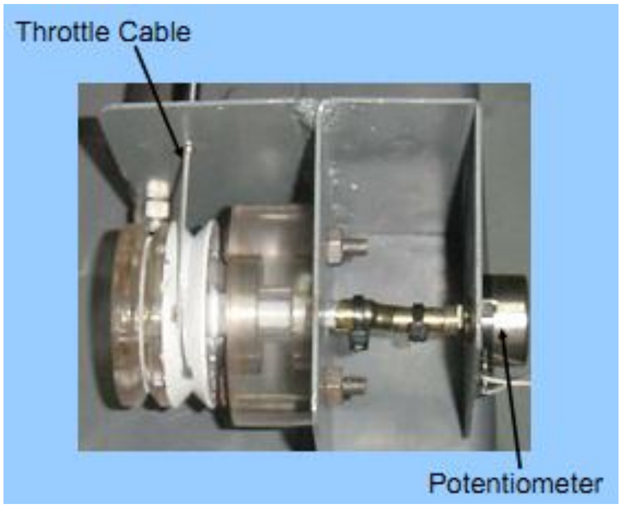

Figure 4 - Throttle And Throttle Sensor Positioning Sourced From (Gitano-Briggs, 2008, P.46)

F. Torque Measurement

Torque measurements were carried out by installing torque flanges coupled to the motor and the output shaft of the gearbox. Tabulation of the rolling radius of the tyre allows the V14 software to calculate the torque being delivered by the engine.

G. Temperature Measurement

Temperature measurements were carried out using a two pronged approach. Temperature of oil, water and intake air were measured utilizing PRT sensors since they afford greater accuracy and resolution at low temperatures. In contrast, exhaust gas temperatures were tabulated using K-type thermocouples since they provide accurate readings up to 1250^{o}C. All temperature readings were integrated through the V14 interface.

H. Data Acquisition

The signals produced by most sensors are analogue and require digital conversion before they can be processed. The sampling rate of the sensors is also of prime importance. Sampling rate was kept at 50 Hz per channel and the sampling was diverted to V14 for processing into CSV format so that data could be extracted and analysed anywhere by a spreadsheet processor.

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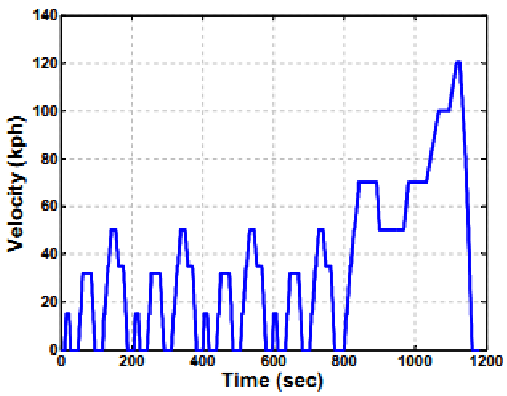
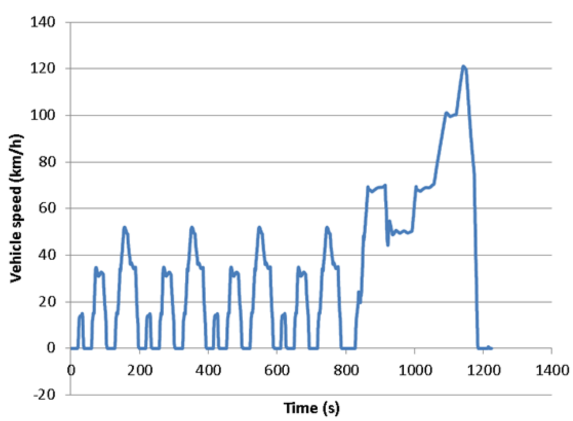
V. Application Of The New European Drive Cycle

A. *New European Drive Cycle*

The NEDC consists of four differentiated cycles of urban driving and one cycle of extra urban driving. The central contention is to emulate the drive cycle which represents different modes of driving in European cities. The urban driving cycle is composed of consecutive accelerations, steady speed patches, decelerations as well as idling patches. The overall combination of these patches allows a replication of the overall drive cycle using an incremental approach. In contrast, the extra urban driving cycle is composed of steady speed testing between 75 km/hr and 120 km/hr as shown in Figure 4(a) below.



(a)

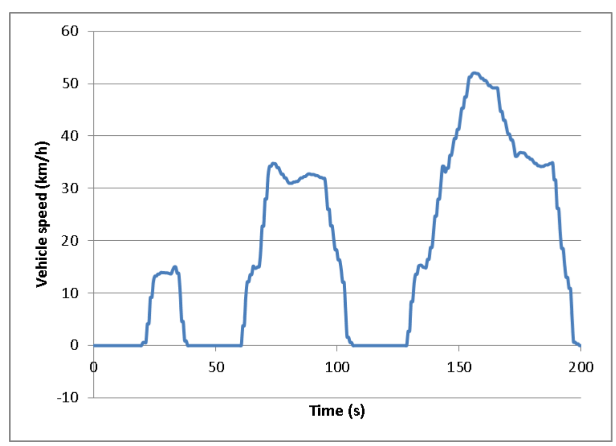


(b)

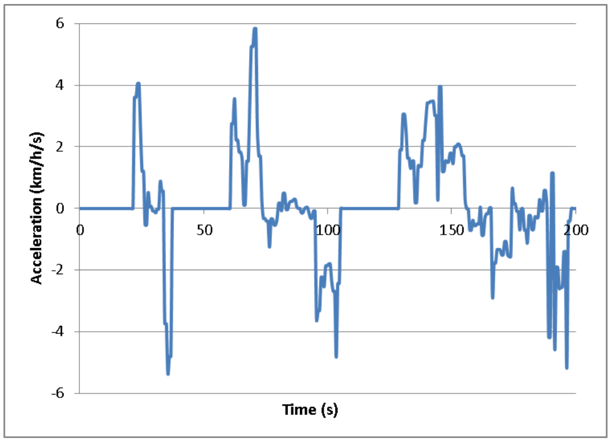
Figure 5 - The New European Drive Cycle (A) As Defined From (Berry, 2007, P. 132), (B) As Simulated Experimentally

B. *Experimental simulation of New European Drive Cycle*

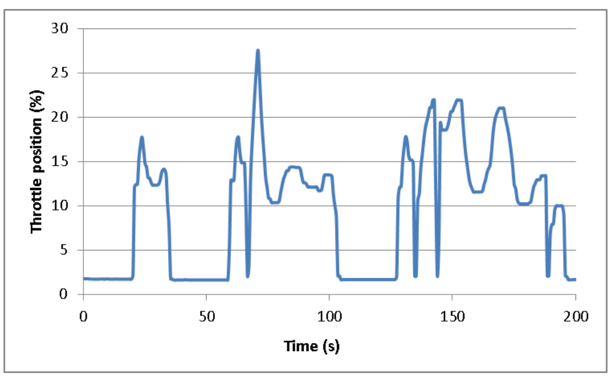
The entire NEDC was simulated in laboratory conditions in order to extract quantifiable results for prediction of fuel consumption. A generator type dynamometer was utilized in order to test the engine to extract data for analysis. The resulting vehicle speed time history is plotted in Figure 5(a), and compared to the defined drive cycle that is shown in Figure 4(a). More details about the first urban driving cycle, i.e. approximately the first 200 s in the NEDC, are provided in Figures 5(a)-(d) showing time histories of of drive-cycle parameters that are the most influencing on fuel consumption, i.e. vehicle speed, acceleration, and throttle position, together with fuel consumption (or more precisely, the fuel mass flow rate in g/s). The various driving modes were utilized in order to tabulate the fuel consumption for the overall driving cycles tested. The average fuel mass flow rate during this cycle is 0.34 g/s. The fuel density is 800 g/l; thus, the consumption is 8.5 l/100 km. The consumption in the further three urban cycles and the last extra-urban cycles are 8.3, 8.2, 8.2 and 5.5 l / 100 km, respectively. The average consumption in the entire NEDC is 6.5 l / 100 km.



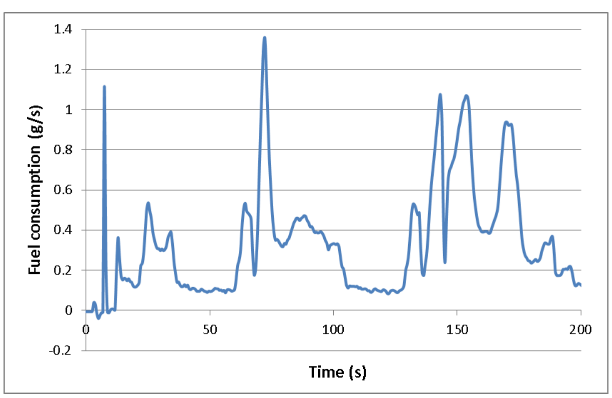
(a)



(b)



(c)



(d)

Figure 6 - Time History Of The Drive-Cycle Parameters During An Urban Drive Cycle Of The Nedc, (A) Vehicle Speed, (B) Acceleration, (C) Throttle Position, (D) Fuel Consumption

VI. Mathematical Model For Prediction Of Fuel Consumption During Drive Cycles

The fuel economy of vehicles can be evaluated via measuring the fuel consumption during drive cycles. The New European Drive Cycle (NEDC) (Berry, 2007) was simulated experimentally and those results are used here to develop an empirical relationship. For the purposes of mathematical modelling the NEDC classifications of urban driving and extra urban driving were decomposed into smaller more quantifiable driving phases as follows:

- constant speed;
- acceleration;
- deceleration due to gradient with throttle;
- deceleration without throttle;
- gear changes.

These phases may be used to construct any random driving cycle that emulates the different kinds of driving conditions and driving behaviour experienced on both urban and extra urban roads. The fuel consumption of any vehicle driven in these phases depends on several different parameters that are used to describe the driving cycle. An examination of multiple factors was carried out to classify which factors made the greatest contributions to fuel consumption. Within the examined parameters, the following parameters were observed to exert a large influence:

- vehicle speed (v);
- acceleration (a);
- throttle position (p);
- gear (G).

These parameters have been used extensively throughout the analysis presented below to propose a mathematical model that can predict fuel consumption (c) in a variety of different driving conditions.

The least squares method is used to fit functions on experimentally obtained data. Different formulae are developed for the five driving phases listed above. Reference values of each recorded parameter; velocity, acceleration, throttle position and fuel consumption (v0, a0, p0, and c0) were determined beforehand and these were then used for relating to the overall relationship. This allowed the creation of mathematical relationships that could be used independently in a number of situations no matter what units were used to express these parameters.

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A. Constant speed

When a passenger car moves with a constant speed, the acceleration is zero, and the throttle position is constant, although this constant depends on the vehicle speed. The fuel consumption in this case is a quadratic function of the vehicle speed. Thus, it can be assumed in the following form:

$$\frac{c}{c_0} = k_{10} + k_{11}\frac{v}{v_0} + k_{12}\left(\frac{v}{v_0}\right)^2 \quad (1)$$

Figure 6 shows measured data in constant speed phases together with the quadratic curve that is fitted on those data using the constants obtained after applying least squares fitting:

k10 = 0.3063;
k11 = 0.6532;
k12 = 2.3913.

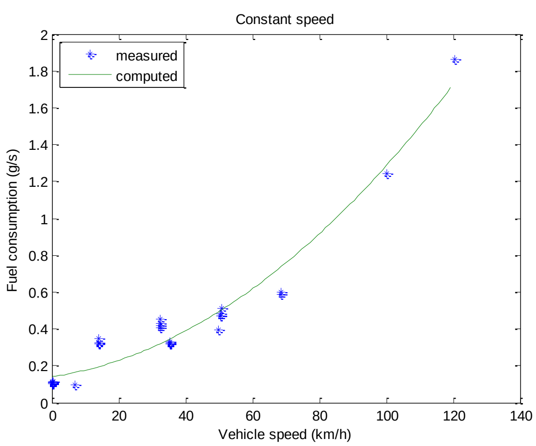

Figure 7 - Fuel Consumption In "Constant Speed" Phases In The New European Drive Cycle

B. Acceleration

In the case of acceleration, the fuel consumption is proportional to the parameter 1/(av)2. The fuel consumption of the vehicle can be assumed to behave in the following form:

$$\frac{c}{c_0} = k_{21}\left(\frac{a_0 v_0^2}{a v^2}\right)^{k_{22}} \quad (2)$$

Figure 7 shows measured data in acceleration phases together with the curve that is fitted on those data with the following constants:

k21 = 10.1739;
k22 = –0.3295.

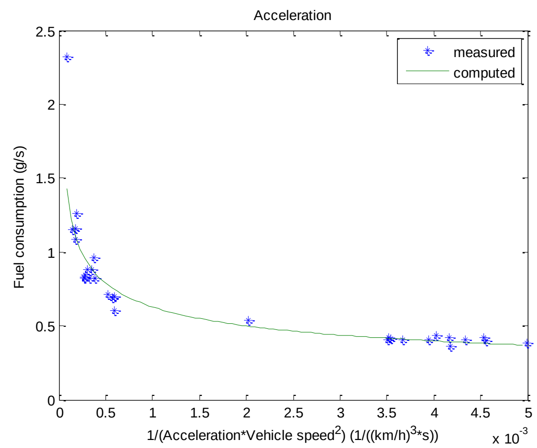

Figure 8 - Fuel Consumption In "Acceleration" Phases In The New European Drive Cycle

C. Deceleration due to gradient with throttle

In the case of decreased throttle opening, the fuel consumption is proportional to the product of throttle position and vehicle speed vp. This indicates that the relationship would be linear in nature and can be expressed in the form of a simple linear equation. Thus, the relationship between throttle opening and fuel consumption for deceleration can be assumed to be of the following form:

$$\frac{c}{c_0} = k_{30} + k_{31}\frac{vp}{v_0 p_0} \quad (3)$$

Fig. 8 shows measured data in deceleration due to gradient with throttle phases together with the curve that is fitted on those data. The corresponding constants are computed as follows:

k30 = 0.4675;
k31 = 14.3461.

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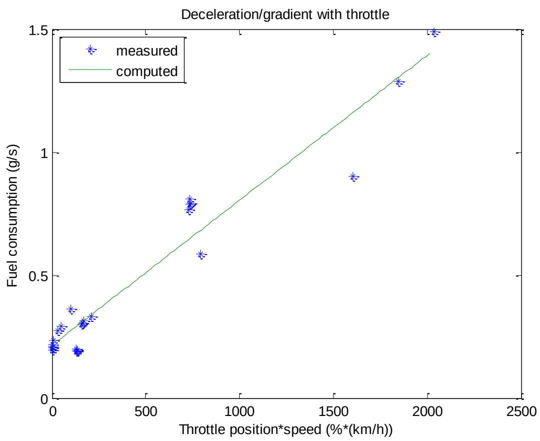

Figure 9 - Fuel Consumption In "Deceleration Due To Gradient With Throttle" Phases In The New European Drive Cycle

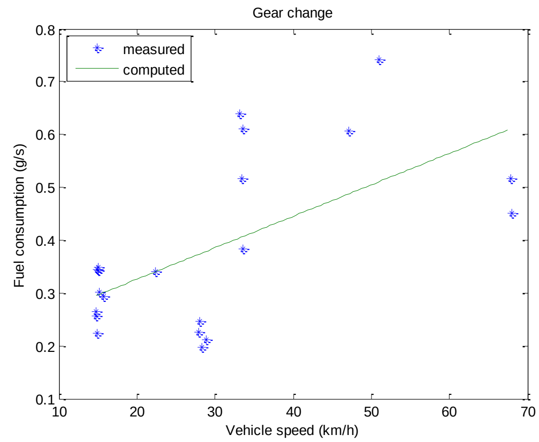

Figure 10 - Fuel Consumption In "Gear Change" Phases In The New European Drive Cycle

D. Deceleration without throttle

The vehicle may slow down while it is still in gear, but the driver released the throttle pedal. In this case, the fuel is not injected, thus, the fuel consumption drops to zero. Finally, the vehicle may slow down while the gear is in neutral. In this case, the fuel consumption is approximately the same as during idling, which is a special case of the constant speed phase, i.e. when the speed is zero.

E. Gear change

During gear change, the consumption may vary considerably, but this variation occurs during quite short time intervals (1-3 s). Therefore, during this phase the consumption is approximated by a linear relationship with vehicle speed in the following form:

$$\frac{c}{c_0} = k_{40} + k_{41}\frac{v}{v_0} \qquad (4)$$

Figure 9 shows measured data in gear change phases together with the curve that is fitted on those data. The corresponding constants are as follows:

k40 = 0.4503;
k41 = 1.4494.

F. Functional representation of the complete drive cycle

The functional relationships proposed in this section can be applied for an arbitrary drive cycle. The drive cycle is divided into short phases, lasting 3-5 s each, and the consumption in each of those short phases is determined by the corresponding formula. Then, the total consumption during the whole cycle can be calculated. The application of the obtained relationships to the NEDC provides a fuel consumption of 12.15 l/100km. The consumption during the same cycle was measured 11.53 l/100km in laboratory. Thus, the error in the prediction using the proposed formula is 5.4%.

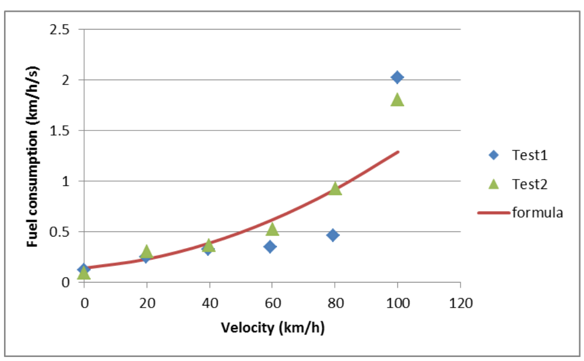

Figure 11 - Fuel Consumption In Constant Speed Phases During Test 1 And Test 2, And Its Prediction By The Mathematical Relationship

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In simple terms, the algorithm derived for fuel consumption calculations based on several constraints and differing situations can be expressed as below:

- The program first examines if the gear changes from the first till last sample in a given short phase, and if so, then equation (4) is used to determine consumption in that phase.
- If the gear does not change (or it is changed from neutral), then velocity variation is investigated. If it is smaller than a prescribed limit (± 2 km/h), then equation (1) is applied to determine consumption.
- If the velocity variation is greater than the prescribed limit, then it is examined whether the acceleration is positive or negative. If it is positive, then equation (2) is used to determine consumption.
- If the acceleration is negative and the gear is in neutral, then equation (1) is used to determine consumption.
- If the acceleration is negative, the gear is not in neutral, and throttle is not applied (or, throttle position is lower than a prescribed limit), then the consumption is zero.
- If the acceleration is negative, the gear is not in neutral, but throttle is applied (or, throttle position is greater than the prescribed limit), then the consumption is determined by equation (3).

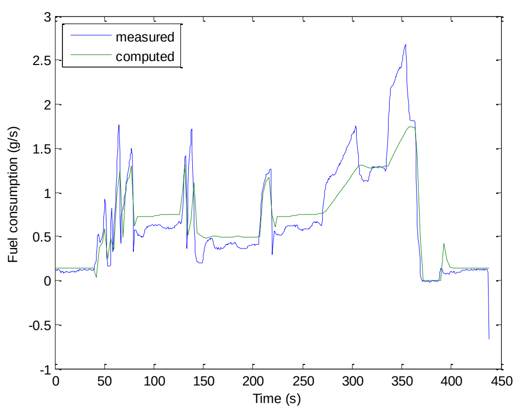

Figure 12 - Measured And Computed Fuel Consumptions During Fifth Sub-Cycle Of Nedc

VII. CONCLUSION

The current paper has looked into the derivation of a mathematical model for the calculation of fuel consumption when applied to the NEDC. Results indicate that both laboratory testing provided reliable validation with the mathematical model proposed above.

The speculated difference between laboratory test results and tabulations of the proposed mathematical model remain around 5%. This indicates good reliability and validity on the part of the mathematical model. The decomposition of the larger driving cycles into short driving phases provides that this method can be used to analyse any driving cycle. In the future, the application of this mathematical model to other drive cycles would also be investigated to determine its applicability.

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